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# Next Generation Astronomical X-ray Optics: High Angular Resolution, Light Weight, and Low Production Cost

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# Mirror Technology Team

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# Current X-ray Telescopes



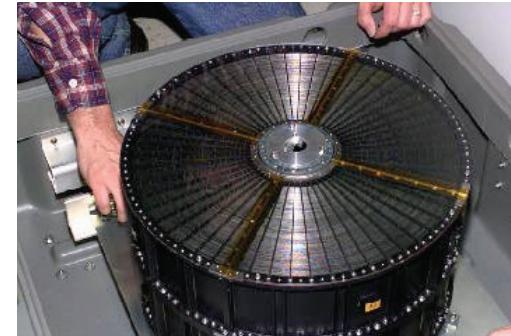
**Chandra**

Zerodur  
Shells



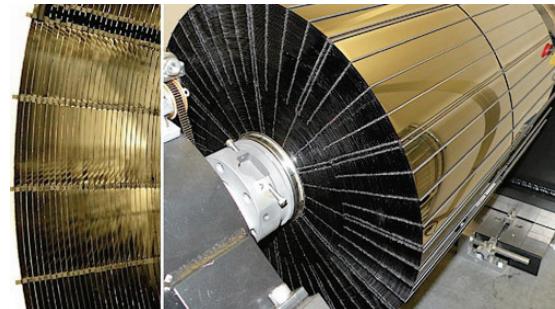
**XMM-Newton**

Electro-formed  
Nickel Shells



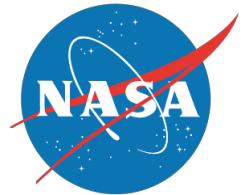
**Suzaku**

Epoxy-replicated aluminum foils

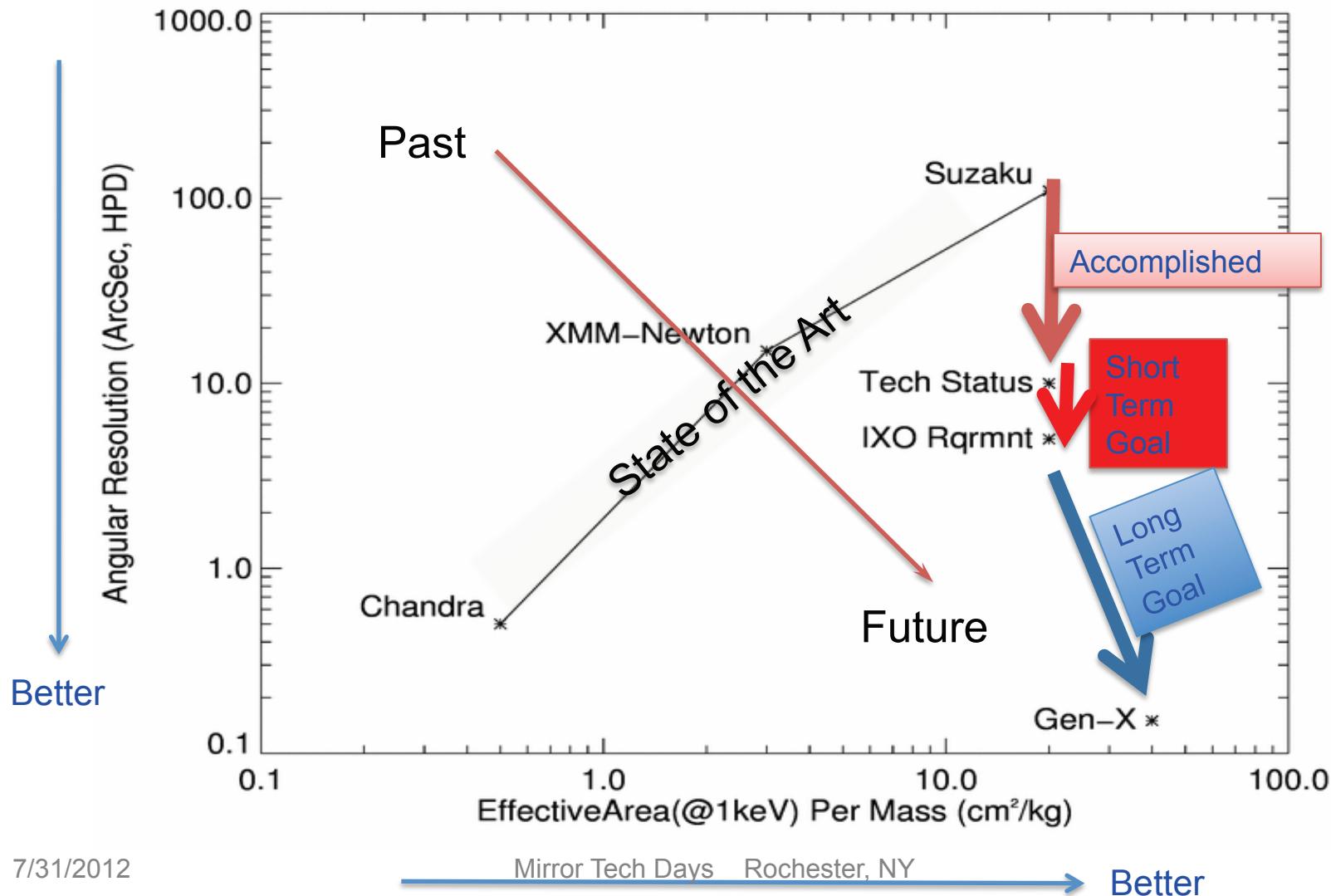


**NuSTAR**

Slumped glass  
segments



# Technology Context

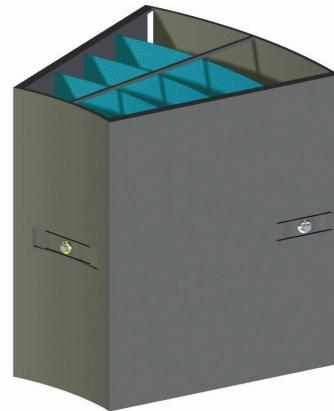




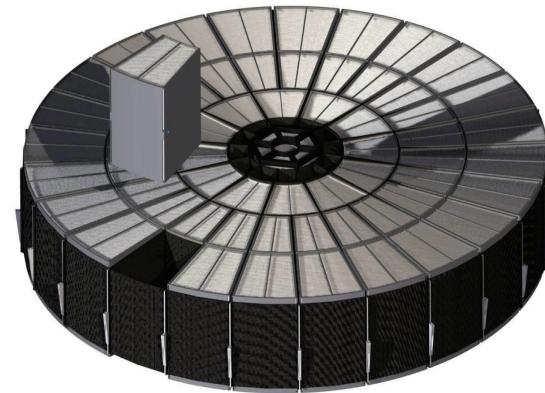
# Process of Building a Telescope



**Fabrication of  
mirror  
segments**



**Integration of  
mirror  
segments into  
mirror module**



**Integration of mirror  
modules into mirror  
assembly**



# Two Core Techniques

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- **Mirror segment fabrication**
  - **Substrate fabrication**
    - Figure
    - Micro-roughness
  - **Coating**
    - Stress
    - Micro-roughness
- **Mirror segment bonding**



# Nature and Challenge of X-ray Optics



- **Grazing Incidence**
- **Nested Concentric Shells**
- **Typical Requirements of a Future X-ray Mission**
  - **Thin:** <0.5 mm
  - **Lightweight:** < 1 kg/m<sup>2</sup>
  - **Large mirror area:** ~1,000 m<sup>2</sup>
    - HST: 4.5 m<sup>2</sup>
    - Chandra: 20 m<sup>2</sup>
    - JWST: 33 m<sup>2</sup>



# Problem and Solutions

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- **Problem:** How to make ~1,000 m<sup>2</sup> of lightweight mirror area for ~\$100M?
- **Two Solutions**
  - **Near term solution:** Slumped glass mirrors
    - A replication process
    - Fully developed and mature
    - Need to reduce forming mandrel cost
  - **Long term solution:** Thin and lightweight mono-crystalline silicon mirrors



# Mirror Substrate Fabrication: Slumping

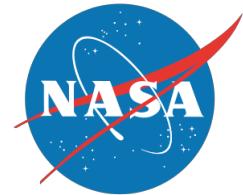
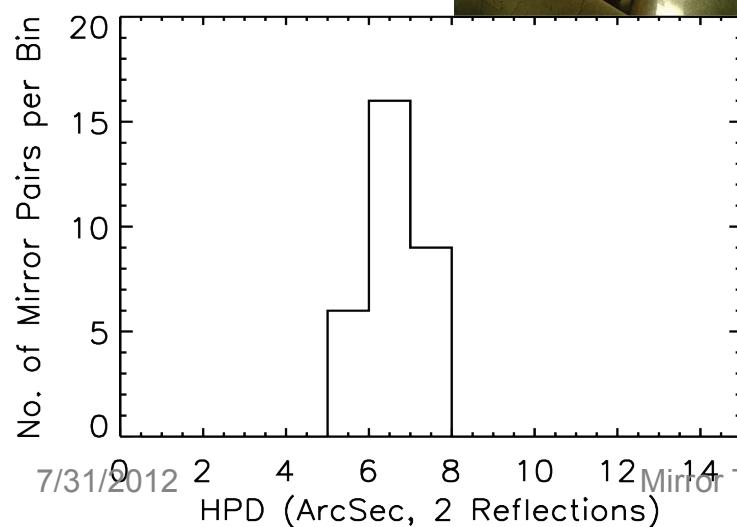


Illustration of glass slumping process

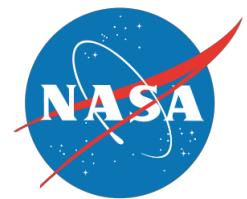
Glass slumping laboratory in  
Bldg 22 of GSFC



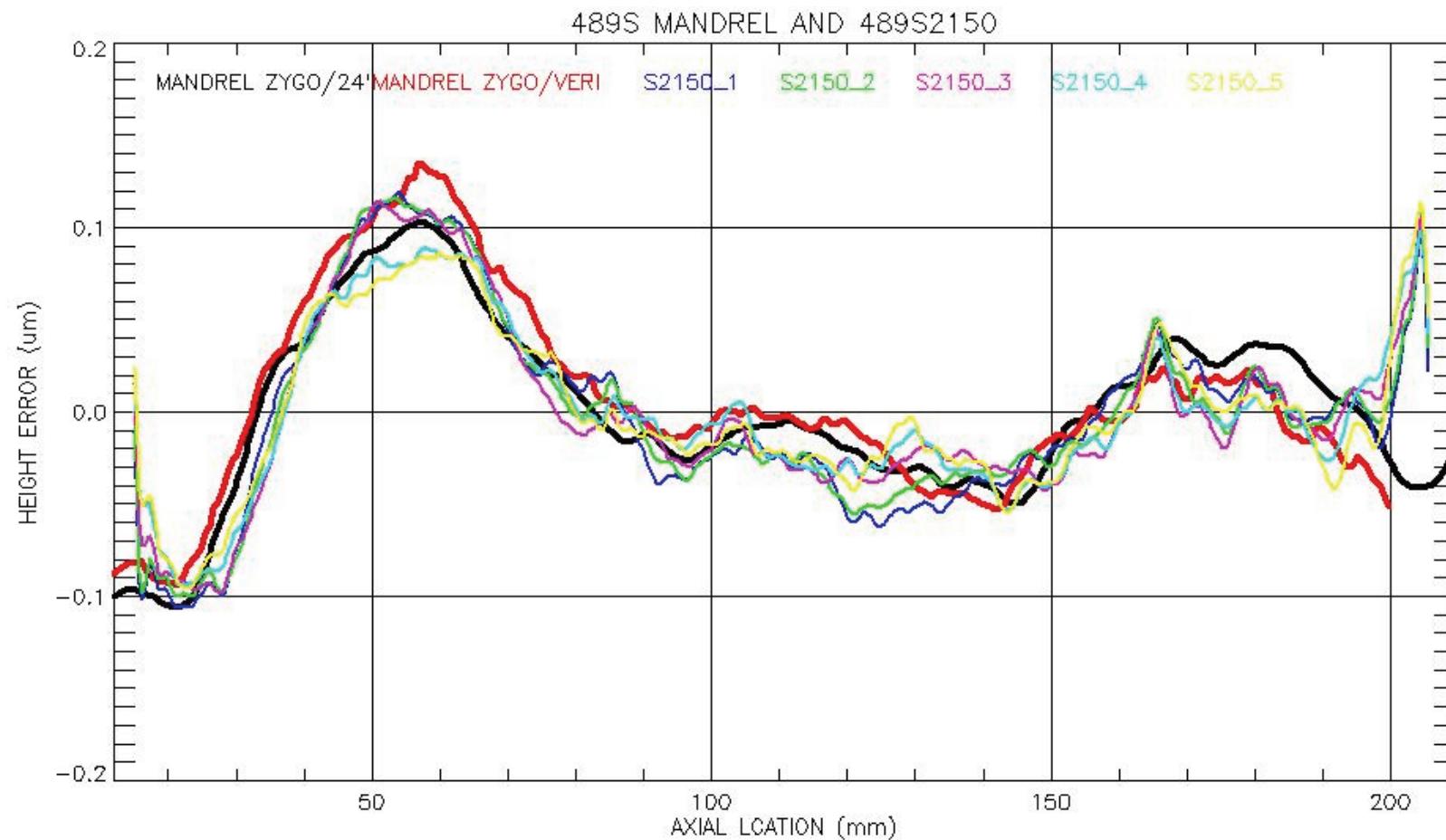
Distribution  
of HPD of  
recent mirror  
substrates



- Best mirror substrates are ~4" HPD (2 reflections)
- Reliably and consistently making 6.5" HPD (2 reflections) substrates
- Mass production capability demonstrated with NuSTAR
- Expect to consistently make 5" substrates by end of 2013

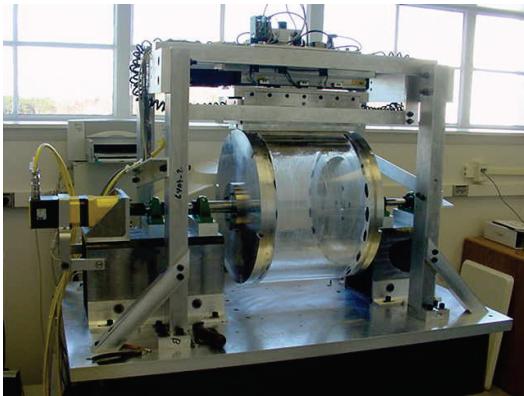


## Comparison between Mirror Segment and Mandrel





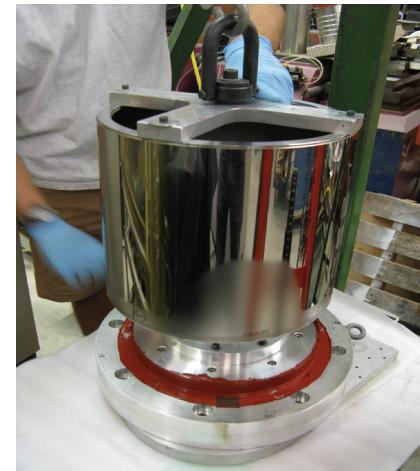
# Fabrication of Forming Mandrels



A full shell mandrel being figured at GSFC



One of four segmented mandrel blanks waiting to be figured

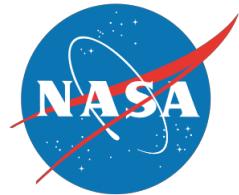


A stainless steel mandrel diamond-turned by DOS

- **Full shell mandrels**
  - fused quartz ones being made at GSFC
  - High temperature alloy ones being made by Dallas Optical Systems
- **Segmented fused quartz mandrels**
  - Fused quartz ones being made at Chubu University, Japan using ZEEKO's Intelligent Robotic Polishers



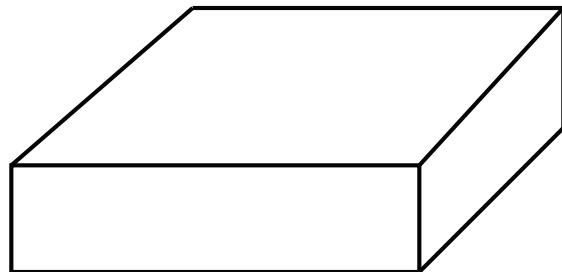
# Two Developments Since Chandra



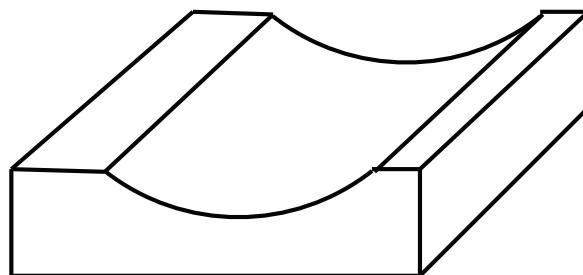
- Deterministic polishing machines have become commercially available
  - QED: Magneto-Rheological Finishing (MRF)
  - ZEEKO: Intelligent Robotic Polishing (IRP)
  - Others....
- Large blocks of mono-crystalline silicon have become easily and cheaply available
  - “Perfect” single crystals – “Free” of internal stress
  - High thermal conductivity and relatively low CTE
  - Can be machined using precision wire-EDM



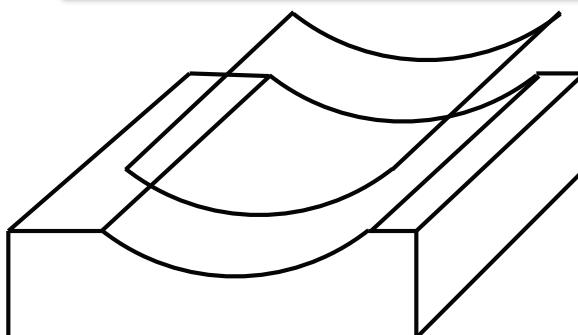
# Lightweight Single Crystal Silicon Mirrors



1. Procure mono-crystalline silicon: easy and cheaply available.
2. Apply heat and chemical treatments to remove all surface/subsurface damage



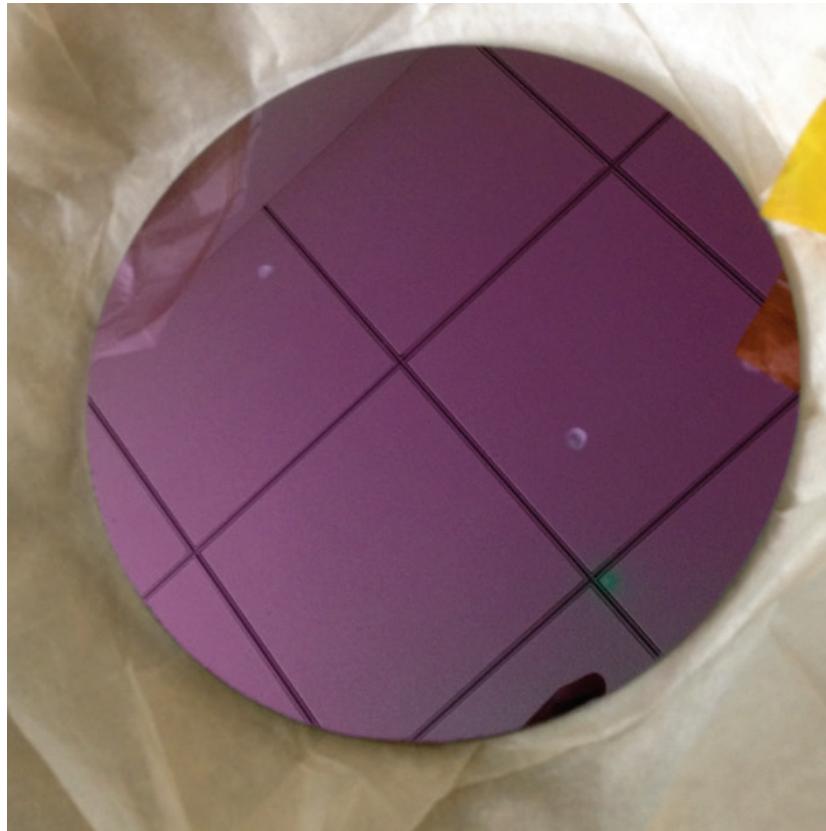
1. W-EDM machine conical shape.
2. Apply heat and chemical treatments to remove damage.
3. Polish using a state of the art technique (e.g., MRF, IRP) to achieve excellent figure and micro-roughness



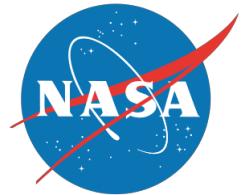
1. Slice off the thin mirror segment
2. Apply heat and chemical treatment to remove all damage from back and edges



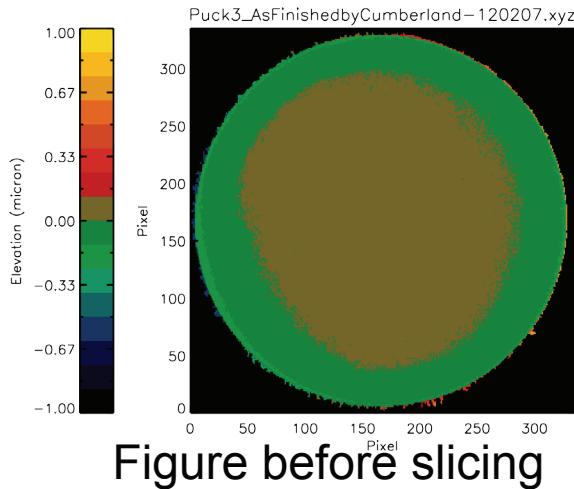
# Progression of Work



- Demonstrate principle using flat mirrors – 2012
  - Polish a thick 55mm flat mirror
  - Slice off a wafer ~1mm thick
- Make separate parabolic/ hyperbolic segments or combined P-H segment
  - Topic for a future presentation

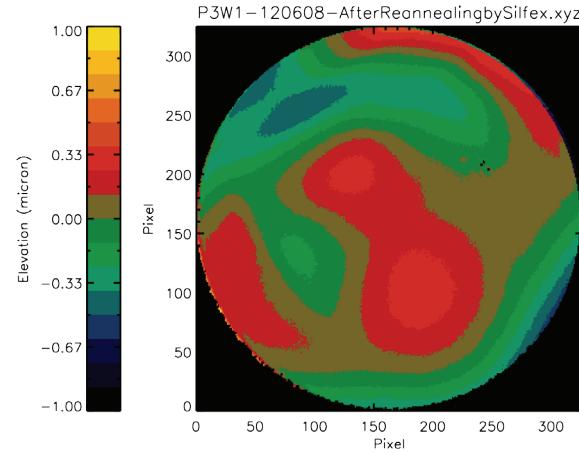
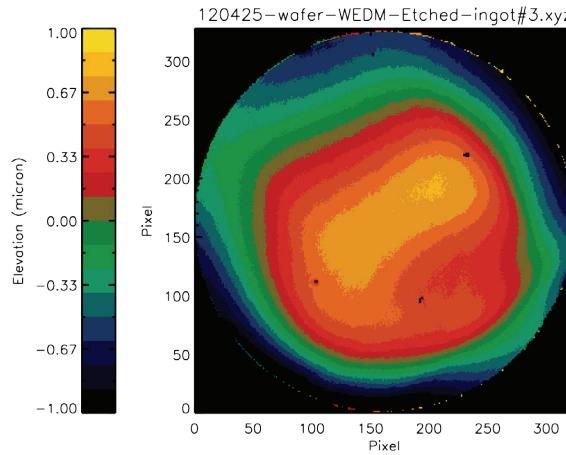


# Initial Result from a Flat Mirror



Not  
Measurable

After slicing





# Future Work

- **Near term – Slumped glass mirrors**
  - Perfect the glass slumping process
  - Reduce forming mandrel cost and schedule
- **Long term – Figured and lightweighted single crystal silicon mirrors**
  - Proof of concept by making flat mirrors
  - Make lightweight Wolter-I mirrors
  - Industrialize the process to make silicon mirrors quickly and cheaply